

**IN THE UNITED STATES PATENT & TRADEMARK OFFICE**

**United States Patent Application**

**For**

**Downhole Flow Meter**

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August 20, 2003  
Date

  
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## DOWNHOLE FLOW METER

This application is a divisional of U.S. Application No. 09/672,471 filed on September 28, 2000, which claims priority under 35 USC 119(e) to U.S. Provisional  
5 Application Serial No. 60/195,831 filed on April 11, 2000.

### Background

This invention relates generally to flow meters used in the downhole environment. Specifically, this invention relates to downhole flow meters that operate by measuring the pressure drop across a variable orifice valve.

10 Downhole flow metering is an essential component of reservoir monitoring. As the industry has moved toward permanent monitoring and control in real time, flow rate, pressure, temperature, resistivity, and watercut, among others, have become important components for assessing well performance.

To measure flow rates, a variety of sensors either on a standalone basis or in  
15 combination have been deployed. These include spinner tools, venturis, gradiomanometers, electromagnetic, acoustic, tracer detectors and gamma-ray sensors. However, these tools are expensive. Permanent downhole deployment of these sensors, especially when individual zone flow rates in multi-zone wells are desired, would require a large monetary investment.

20 Flow rate measurements may be used for a variety of purposes. The primary use is to help in quantifying produced fluids. In wellbores having multiple completions with feedback control, it may be desirable to set flow rates or pressure for the various zones so as to optimize the productivity. It is then necessary to measure the flow or pressure rate

in each zone, compare them to a set point, and adjust the aperture openings in the valves of each zone completion in order to maintain flow rate or pressure as close to the desired value as possible.

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### Summary

This invention comprises the use of a variable orifice valve as a flow controller and flow meter. Pressure measurements are taken upstream and downstream of the variable orifice valve (across the valve) by way of a differential pressure measurement mechanism. The differential pressure measurement mechanism may comprise two separate absolute pressure measurement devices or a single differential pressure measurement device. Flow rate through the valve is determined from the pressure drop across the valve. In wellbores having multiple zones, a variable orifice valve together with a differential pressure measurement mechanism may be deployed for each zone. The flow rate through each of the zones, in the completion tubing, and at the surface can then be monitored and controlled.

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### Brief Description of the Drawings

Figure 1 is a view of a wellbore having multiple zones with a flow meter disposed for each zone.

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Figure 2 is a cross-sectional view of the flow meter.

Detailed Description

Figure 1 shows a wellbore 10 that may include a casing 12 or liner 80 and that includes a tubing string 14 disposed therein. An annulus 13 is defined exterior to the tubing string 14. Figure 1 shows a plurality of zones 90 included in the wellbore 10. A flow meter 15 is incorporated into the tubing string 14 for each zone 90. Although Figure 1 shows a wellbore 10 that includes multiple zones 90 (each having its own flow meter 15), it is understood that a single flow meter 15 may be disposed in a wellbore having only one zone 90 or that a single flow meter 15 may be disposed in a wellbore having multiple zones 90. It is also understood that a flow meter 15 may be disposed in the lateral bores of wellbores.

Each flow meter 15 is preferably proximate a formation 90. Typically, the wellbore 10 is perforated to provide fluid communication between each formation 90 and the wellbore 10 through perforations 92. Packers 94 are normally used to isolate each formation 90. The fluid flowing from a formation 90 and being measured by flow meter 15 may be in any of various phases, including single phase liquid or gas, two phase oil/water, two phase liquid/gas, or multi-phase.

*A. Flow Meter*

Figure 2 shows the flow meter 15 in more detail. In general, the flow meter 15 of this invention comprises a variable orifice valve 16 and a differential pressure measurement mechanism 18.

In the embodiment shown in Figure 2, variable orifice valve 16 comprises a side pocket sleeve valve 17. However, variable orifice valve 16 may also comprise other

types of valves, such as disc valves and butterfly valves. In one embodiment as shown in the Figures, variable orifice valve 16 is installed in a side pocket mandrel. In other embodiments (not shown), variable orifice valve 16 is a part of the main bore of the tubing string 14.

5 Variable orifice valve 16 provides fluid communication between the annulus 13 and the interior of the tubing string 14 through at least one opening 19. Variable orifice valve 16 preferably includes a plurality of settings between fully closed and fully open, each setting exposing a different amount of surface area of the opening(s) 19 to flow and thus allowing a different flow volume through valve 16.

10 The differential pressure measurement mechanism 18 measures the pressure drop across the variable orifice valve 16. In one embodiment as shown in Figure 2, the differential pressure measurement mechanism 18 comprises a differential pressure measurement device 23 located so that it can measure the pressure within the bore 24 of the tubing string 14 as well as within the annulus 13. Adequate differential pressure measurement devices 23 include differential pressure gauges, such as Schlumberger's gradiomanometer tool. In another embodiment (not shown), the differential pressure measurement mechanism 18 comprises a separate outer pressure measurement device and inner pressure measurement device, each comprising a measurement device such as an absolute pressure gauge. The outer pressure measurement device is located so that it  
15 measures the pressure within the annulus 13. Preferably, the outer pressure measurement device is located within the annulus 13 proximate the variable orifice valve 16. The inner pressure measurement device is located so that it measures the pressure within the bore  
20

24 of the tubing string 14. Preferably, the inner pressure measurement device is located within the bore 24 of the tubing string 14 also proximate the variable orifice valve 16.

In one embodiment, each variable orifice valve 16 is controlled, as shown in Figure 2, by hydraulic pressure from the surface through at least one hydraulic control line 30. In other embodiments (not shown), each variable orifice valve 16 may be controlled by electrical conduits, pressure pulse telemetry, acoustic telemetry, or electro-magnetic telemetry.

In one embodiment, each differential pressure measurement mechanism 18 is powered by at least one electrical conduit 32, which may also serve to transfer the readings of the mechanism 18 to the surface. In other embodiments (not shown), each differential pressure measurement mechanism 18 is powered by a battery located downhole, and the readings may be transferred to the surface by way of electrical conduits, pressure pulse telemetry, acoustic telemetry, or electro-magnetic telemetry.

#### 15      *B. Liquid Flow Rate Equation*

The flow rate of a single phase liquid across each variable orifice valve 16 can be determined by use of the following fluid dynamics Equation [1] or an equivalent thereof:

$$Q = C A \varepsilon \sqrt{\frac{2 \Delta P}{\rho}}$$

where  $Q$  = flow rate,  $C$  = flow coefficient (this variable depends on a number of factors as will be explained herein),  $A$  = total area of variable orifice valve openings 19 that are exposed to flow,  $\varepsilon$  = expansibility factor,  $\Delta P$  = pressure drop, and  $\rho$  = upstream fluid density.

To calculate flow rate ( $Q$ ) using Equation [1], the pressure drop ( $\Delta P$ ) is measured from the downhole readings of the differential pressure measurement mechanism 18, as previously described. For single phase liquid flow, the expansibility factor ( $\varepsilon$ ) can be approximated to equal 1.

5 The fluid density ( $\rho$ ) can be determined based on the prevailing P, T and the PVT  
properties of the fluid. In one embodiment, the PVT calculation is performed by taking a  
relevant fluid sample downhole, bringing the sample to the surface, and analyzing it. In  
another embodiment, the relevant calculation is performed by flowing only the flow  
meter 15 that includes the relevant variable orifice valve 16, taking a sample of the fluid  
10 at the surface, and analyzing the sample at the surface. In yet another embodiment, the  
fluid density ( $\rho$ ) can be obtained from a gradiomanometer measurement or other density  
measuring devices, such as gamma densitometers and capacitance/resistance devices.

In one embodiment, the total area of exposed variable orifice valve openings ( $A$ ) is determined by measurement at the surface. As previously stated, variable orifice valve 15 16 preferably includes more than one position between fully opened and fully closed. The total area of exposed variable orifice valve openings ( $A$ ) should therefore be determined for each position or setting.

For valves having openings 19 that are identical, the total area of exposed variable orifice valve openings ( $A$ ) can be represented by the following Equation [2]:

$$20 \hspace{10cm} A = n_o a$$

where  $n_o$  is the number of openings 19 that are exposed to the flow, and  $a$  is the area of each opening 19.

For a given stem position  $h$  of valve 16, the area ( $a$ ) of each opening 19 exposed to the flow may be stated as a general Equation [3]:

$$a = f_a(h) \approx \gamma h^\alpha, \alpha > 0$$

where  $\gamma$  and  $\alpha$  are characterizing parameters and  $h$  is a variable representing the stem

- 5 position of valve 16 for a given setting. The stem position variable ( $h$ ) is known from the level of valve 16 actuation performed or from a position transducer mounted on valve 16.

In general, Equation [3] may drift with time due to erosion. Unfortunately, the erosion process is not adequately captured by parameters  $\gamma$  and  $\alpha$ . For example, erosion may affect the fully opened or fully closed positions more than some intermediate settings.

- 10 Therefore, a more general monotonic function may be preferable. A reasonable Equation [4] to use is:

$$\frac{a}{a_0} = \frac{x_h^z}{\sqrt{(v + (1 - v)x_h^{2z})}}$$

where  $a_0$  is the area per opening when the valve 16 is in the fully open position,  $x_h$  is the fractional stem movement which equals  $h/h_{max}$ , and  $v$  and  $z$  are characterizing parameters.

- 15 The remaining parameter required to determine flow rate using Equation [1] is the flow coefficient ( $C$ ), which is dependent on the following parameters:

$$C = C_f(\text{Re}, \frac{A_u}{a}, \frac{A_d}{a}, \text{pressure} \cdot \text{tap} \cdot \text{locations})$$

where  $\text{Re}$  is the Reynold's Number defined at a reliable position (for example the throat),  $A_u$  is the area upstream of valve 16 (the area exposed to the formation), and  $A_d$  is the area

downstream of valve 16 (approximately equal to the cross-sectional area of the tubing string bore 24).

Since the flow coefficient ( $C$ ) cannot be calculated with any certainty using equations, it must be determined through experimentation and/or mathematical modeling.

- 5 The flow coefficient must be determined for each setting of valve 16. The flow coefficient ( $C$ ) can be experimentally determined when the flow meter 15 is already downhole or prior to downhole deployment of the flow meter 15.

To conduct the experiment when the flow meter 15 is already in the downhole environment, the variable orifice valve 16 of the relevant flow meter 15 is opened to one 10 of its settings thus allowing flow of fluids through the variable orifice valve 16, within tubing string 14, and to the surface. If more than one flow meter 15 is included in the wellbore, only the variable orifice valve 16 of the flow meter 15 being characterized is opened. The flow rate ( $Q$ ) of the fluid is then measured at the surface or by an independent flow metering device downstream (e.g. spinner, etc.). Knowing the values 15 of all the relevant variables of Equation [1], Equation [1] is solved for the flow coefficient ( $C$ ). This procedure is repeated for each setting of valve 16 (and for each valve 16).

To conduct the experiment prior to the downhole deployment of the flow meter 15, the flow meter 15 is connected to a laboratory simulator or a flow loop, wherein the 20 flow of fluids through the variable orifice valve 16 is simulated. All of the relevant variables of Equation [1] will be known or measurable, including the flow rate ( $Q$ ). Knowing the values of all the relevant variables of Equation [1], Equation [1] is solved

for the flow coefficient ( $C$ ). This procedure is repeated for each setting of valve 16 (and for each valve 16).

*C. Flow Rate Calculation*

5 In general, formation fluid flows from a formation 90, through perforations 92, into the annulus 13, through the variable orifice valve 16 (at a specified setting), and into the bore 24 of the tubing string 14. The fluid then flows within bore 24 to the surface of the wellbore 10.

The calculation of flow rate across a single flow meter 15 disposed in a flowing wellbore 10 is straight forward. Essentially, the pressure readings from the differential pressure measurement mechanism 18 are taken real-time or at designated intervals and are transmitted to the surface. The flow coefficient ( $C$ ), total area of variable orifice valve openings 19 that are exposed to flow ( $A$ ), expansibility factor ( $\epsilon$ ), and upstream fluid density ( $\rho$ ) are each determined by the methods previously stated. It is noted that 10 the flow coefficient ( $C$ ) and the total area of variable orifice valve openings 19 exposed to flow ( $A$ ) are different for each setting of valve 16. Knowing each of these variables, 15 Equation [1] can then be easily applied to get the flow rate ( $Q$ ) through the valve.

In one embodiment, the pressure readings from the differential pressure measurement mechanism 18 are transmitted to a surface processor, such as a computer.

20 The surface processor also stores Equation [1] and its relevant other variables and can thus calculate the flow rate through the relevant valve 16 by using Equation [1], as previously disclosed.

In another embodiment, the pressure readings from the differential pressure measurement mechanism 18 are recorded within a recorder deployed downhole. The readings may be subsequently retrieved to the surface and plugged into Equation [1].

In those embodiments including more than one flow meter 15 such as that shown  
5 in Figure 1, the pressure downstream of each valve 16 is related to the flow entering  
through the valve 16 and the main flow passing through the tubing string 14. Thus the  
downstream pressure at each valve 16 controls both the flow through the valve 16 and the  
total flow up to that point in the tubing string 14. Consequently, the flow through each  
valve 16 is intimately related to the others. Preferably, a mathematical flow model of the  
10 whole wellbore 10 is designed, incorporating the required flow rates, formation pressures,  
valve settings, well head pressure, valve losses and pipe losses. This model is utilized to  
predict the flow rate and the pressure throughout the wellbore 10.

15      *D. Gas Flow Rate Equation and Calculation*

The flow rate of a single phase gas flow across each variable orifice valve 16 can  
also be determined by use of Equation [1] or an equivalent thereof. However, unlike the  
calculation for single phase liquid flow wherein the expansibility factor ( $\varepsilon$ ) can be  
approximated to equal 1, the expansibility factor ( $\varepsilon$ ) for single phase gas flow cannot be  
20 approximated and must be determined. For single phase gas flow, the expansibility  
factor ( $\varepsilon$ ) is determined based on the prevailing P, T and the PVT properties of the fluid.  
In one embodiment, the PVT calculation is performed by taking a relevant fluid sample  
downhole, bringing the sample to the surface, and analyzing it. In another embodiment,

the relevant calculation is performed by flowing only the flow meter 15 that includes the relevant variable orifice valve 16, taking a sample of the fluid at the surface, and analyzing the sample at the surface.

The remainder of the flow rate calculation for single phase gas flow is the same as  
 5 the flow rate calculation for single phase liquid flow, as detailed in Sections B and C  
 herein.

#### *E. Oil/Water Flow Rate Equation and Calculation*

For flow having oil and water content, experiments have shown that a few  
 10 diameters downstream of a venturi flow meter, the flow is well mixed, i.e., in water-oil  
 flow, and that the slip velocity is negligible compared to either phase velocity. The  
 holdup is then equal to the fractional flow of the phases. For the drop sizes of the  
 entrained phase, we are expected to have negligible pressure difference between the  
 phases. Therefore, substituting the average density  $\rho_e$  for  $\rho$  in Equation [1] gives the flow  
 15 rate equation for oil/water flow. The average density ( $\rho_e$ ), in turn, can be calculated by  
 the following Equation [5]:

$$\rho_e = \rho_w S_w + \rho_o (1 - S_w)$$

where  $S_w$  is the water holdup (approximately equal to its flow fraction),  $\rho_w$  is the density  
 20 of the water content in the flow, and  $\rho_o$  is the density of the oil content in the flow. In one  
 embodiment, the water content density ( $\rho_w$ ), the oil content density ( $\rho_o$ ), and the water  
 holdup ( $S_w$ ) are calculated by techniques and tools known to the prior art. In another  
 embodiment, a differential pressure measurement along the flowline downstream of the  
 orifice can provide an estimate of the average density ( $\rho_e$ ). The differential pressure

measurement can be obtained by use of standard production logging application tools, such as Schlumberger's Gradio Venturi Meter tool or other fluid density measuring devices, such as gamma densitometers and capacitance/resistance devices. Then, the following Equations [6] can be used as a simple first approximations of the oil content  
 5 flow rate and the water content flow rate:

$$q_w = qS_w \quad \text{and} \quad q_o = q(1-S_w)$$

The remainder of the flow rate calculation for flow that includes oil and water content is the same as the flow rate calculation for single phase liquid flow, as detailed in Sections B and C herein.

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#### *F. Flow Rate Equation and Calculation for Other Phases*

For flow having other types of phasing, such as two phase liquid/gas or multi-phase fluid, the flow rate across valve 16 can also be determined by use of Equation [1] or an equivalent thereof. As previously mentioned with respect to the fluid phases  
 15 described in Sections B-E herein, the variables of Equation [1], including the expansibility factor ( $\varepsilon$ ) and the density ( $\rho$ ) or equivalent density ( $\rho_e$ ), can be determined using tables, known instruments, and/or calibration. Once the variables of Equation [1] are determined sing such methods for the relevant fluid, the remainder of the flow rate calculation is the same as the flow rate calculations described previously.

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#### *G. Subsequent Calibration*

The total area of exposed variable orifice valve openings ( $A$ ) and the flow coefficient ( $C$ ) are likely to vary over a period of time due to erosion of the valve

openings 19, among other things. Thus, to maintain the reliability of the flow rate ( $Q$ ) calculation, the total area of exposed variable orifice valve openings ( $A$ ) and the flow coefficient ( $C$ ) should be re-calibrated from time to time.

In order to re-calibrate such variables, the variable orifice valve 16 of the relevant  
5 flow meter 15 is opened and the surface flow rate ( $Q$ ) is measured. If the wellbore includes more than one flow meter 15, only the variable orifice valve 16 of the relevant flow meter 15 should be opened. All other valves 16 should remain closed.

If Equation [2] is used to calculate the total area of exposed variable orifice valve openings ( $A$ ) for the relevant variable orifice valve 16, then Equations [1] and [2] can be  
10 combined into the following Equation [6]:

$$Q = Cn_0 a \varepsilon \sqrt{\frac{2\Delta P}{\rho}}$$

The variable orifice valve 16 is opened to each of its settings and the surface flow rate ( $Q$ ) is measured at each setting. Equation [6] is then solved for the product of the flow coefficient ( $C$ ) and the area ( $a$ ) of each opening 19 for each of the settings of variable  
15 orifice valve 16 (note  $n_0$  is a known variable). This technique can also be used when, as in Equation [1], only the variable ( $A$ ) is used (instead of also using Equations [2], [3], or [4]), wherein Equation [1] would be solved for the product of the flow coefficient ( $C$ ) and the total area of exposed variable orifice valve openings ( $A$ ) for each setting of valve 16.

If Equation [3] is used to calculate the total area of exposed variable orifice valve  
20 openings ( $A$ ) for the relevant variable orifice valve 16, then Equations [1] and [3] can be combined into the following Equation [7]:

$$Q = Cn_0 \gamma h^\alpha \varepsilon \sqrt{\frac{2\Delta P}{\rho}}$$

- The variable orifice valve 16 is then opened to two distinct settings and the surface flow rate ( $Q$ ) is measured for each of the two settings. With two Equations [7] (one for each setting), the desired parameters  $C\gamma$  and  $\alpha$  can be calculated thus providing the re-calibrated values.

If Equation [4] is used to calculate the total area of exposed variable orifice valve openings ( $A$ ) for the relevant variable orifice valve 16, then Equations [1] and [4] can be combined into the following Equation [8]:

$$Q = \frac{Cn_0 \varepsilon a_0 x_h^z}{\sqrt{\nu + (1-\nu)x_h^{2z}}} \sqrt{\frac{2\Delta P}{\rho}}$$

- The variable orifice valve 16 is then opened to three distinct settings and the surface flow rate ( $Q$ ) is measured for each of the three settings. With three Equations [8] (one for each setting), the desired parameters  $C$ ,  $z$ , and  $\nu$  can be calculated thus providing the re-calibrated values.

In any case, a venturi may also be included in the tubing string 14 above all of the zones 90. The venturi measures the total flow from all zones 90. By testing each zone 90 individually (as above), the flow measured across each valve 16 may then be compared to the theoretical flow and the venturi flow, which comparison (with the aid of time lapse trending) would provide an indication of the performance of the valve, including the effects of erosion or hysteresis.

In view of the foregoing it is evident that the present invention is one well adapted to attain all of the objects and features hereinabove set forth, together with other objects and features which are inherent in the apparatus disclosed herein.

As will be readily apparent to those skilled in the art, the present invention may  
5 easily be produced in other specific forms without departing from its spirit or essential characteristics. The present embodiment is, therefore, to be considered as merely illustrative and not restrictive, the scope of the invention being indicated by the claims rather than the foregoing description, and all changes which come within the meaning and range of equivalence of the claims are therefore intended to be embraced therein.